

Magnetic Monopole Bibliography

G. Giacomelli¹, M. Giorgini¹, T. Lari¹, M. Ouchrif^{1,2},
L. Patrizzii¹, V. Popa^{1,3}, P. Spada¹ and V. Togo¹

¹*Dipartimento di Fisica dell'Università di Bologna and INFN, Sezione di
Bologna, I-40127 Bologna, Italy*

²*Faculty of Sciences, University Mohamed I, B.P. 524 Oujda, Morocco*

³*Institute of Space Sciences, Bucharest R-76900, Romania*

Abstract

We present a bibliography compilation on magnetic monopoles updated to include references till the end of year 1999. It is intended to contain nearly all the experimental papers on the subject and only the theoretical papers which have some specific experimental implications.

1. Introduction

Even though Maxwell's equations formally allow the existence of magnetic monopoles (MMs), interest in this kind of objects arose only in 1931 after the paper of P. A. M. Dirac [31D1], in which it was shown that magnetic charges can be introduced in the framework of quantum mechanics and that the product of the basic electric charge and of the basic magnetic charge is quantized according to the Dirac relation $eg = \frac{n\hbar c}{2}$, where n is an integer. Such a particle is called *magnetic monopole* if it carries only a magnetic charge, and *dyon* if it carries both magnetic and electric charges (a monopole bound with a nucleus behaves effectively as a dyon). Dirac could not constrain the monopole mass; rough estimates indicated that the MM mass should be larger than several GeV.

Many types of searches for magnetic monopoles with masses not much larger than the proton mass were performed at each new accelerator and in bulk matter. Very many theoretical studies on MMs have been published.

The other date of fundamental importance in the history of monopoles is 1974. In that year 't Hooft [74H1] and Polyakov [74P1] demonstrated that Grand Unified Theories (GUT) of the electroweak and strong interactions implied the existence of MMs with masses of the order of 10^{17} GeV/c² ($m_M \sim m_X/\alpha$ where m_X is the mass of the carrier of the unified force and α is the unified coupling constant). These masses are too large for monopoles to be produced at present or future high energy accelerators or somewhere in the present universe. They could have been produced immediately after the big bang, either as topological defects or in very high energy collisions such as $e^+e^- \rightarrow M\bar{M}$, immediately after the phase transition at the end of the GUT epoch; thus GUT monopoles could be present in the cosmic radiation, since the lightest monopole should be stable, due to conservation of magnetic charge. From 1974 to the present time a very large number of theoretical studies were made on magnetic monopoles; also many experimental searches were performed.

The present paper gives a bibliography of publications on monopoles. The bibliography is intended to contain nearly all the experimental papers on the subject and only the theoretical papers which have specific experimental implications. With some exceptions only papers published in international refereed journals have been included.

The publications on MMs comprise many different subjects.

1) Theoretical works on Dirac MMs (for ex. [31D1], [66S1], [76W1], [77K2], [97I2], ...). The possible existence of bound states of magnetic monopoles with electrons and/or nuclei has also been investigated (for ex. [51M1], [77K3], [83B1], [83B2], [84B1], ...).

2) Theoretical works on GUT MMs (for ex. [74H1], [74P1], [84P1], ...).

3) Papers on the catalysis of baryon decay by GUT monopoles, such as [80R1], [82C2].

4) Papers on the cosmological production of MMs (for ex. [76K1], [79P1], [80L2], [80E1], [81G2], ...) and papers which derived limits on MM fluxes from astrophysical considerations (for ex. [70P1], [82K2], [85A2], [85B2], ...).

5) Theoretical works on supermassive MMs based on other theories, like monopoles from superstrings ([87L1]), intermediate symmetry breaking monopoles ([83L1], [84L2]), or lighter monopoles of electroweak nature ([97C1], [97C4]).

6) Studies of the energy losses of monopoles in matter and on the possible techniques to detect them (for ex. [78A1], [82A4], [83A2], [83D3], [84B2], [85B5], [87F1], [89P1], [91O1], [97A1], ...).

7) Searches at high energy accelerators; the searches are either *direct* (detection of monopoles immediately after their production in high-energy collisions) or *indirect* (for example when a piece of matter is exposed to a beam for a long time, and then later analyzed). Examples of direct searches are [75G1], [82K1], [83A7], [83M1], [87G2], [90B3], [00B2], ... Examples of indirect searches are [61F1], [63A1], [66A1], [74C1], [75E1], [78C1], [83B7],

8) Searches for possible effects of virtual monopoles, such as [95D2], [95A2], [97K2], ...

9) Direct searches for MMs in the cosmic radiation. Examples of such searches are those by MACRO [91B1], [91P1], [94A1], [95A1], [95M2], [97A2], [97A3] and by other experiments [82B2], [83C1], [86P1], [90B1], [90B2], [90B4], [90G1], [91O1], [92T1].

10) Indirect searches for monopoles in the cosmic radiation; the experiments look for monopoles trapped in matter or for the effects due to the passage of MMs in the past. Examples are [63G2], [73R1], [83E1], [84P3], [86P1], [87E1], [89A1], [90G1], [95J1], ...

11) Review papers on various aspects of monopoles and on their experimental search; examples are [81G3], [82G1], [83P1], [86G2], [94G1], [96B3], ...

Several MM bibliographies have been made in the past, see [73S1], [77C1], [80R1], [82C4], [84G1], [94G1]. The bibliography in [84G1] is more complete than the present one for the period before 1984. The bibliography of [80R1] covers essentially all the papers dealing with classical Dirac monopoles.

A bibliography on the experimental limits and on astrophysical bounds is presented regularly every two years by the Particle Data Group (see [96P1], [94P2], [92P1]).

The present bibliography covers the period before May 2000 and is an update of DFUB 98-9 [98G6].

Fig. 1a presents an histogram with the number of papers on MMs and dyons published each year from 1973 to 1983 [83P1]; Fig. 1b shows the number of papers in the present bibliography (until December 1999) as a function of the year of publication; Fig. 1c shows an histogram of the number of yearly papers in the SLAC database which meet one of the following conditions:

- they have *monopole* or *monopoles* in the title;
- they have *dyon* or *dyons* or *dyonic* in the title;
- they have the keyword *magnetic monopole* assigned.

For the first and second histogram the year is that of publication, for the third it is the year of receipt by the SLAC library; this third histogram has many more entries, mostly theoretical papers, conference proceedings and unpublished reports.

The peak rates in the histograms correspond to the periods immediately after the paper of 't Hooft and Polyakov (1974) and after the 1982 Cabrera candidate event.

Fig. 2 shows a compilation of the 90% C.L. limits on MMs in the cosmic radiation; the limits apply to an isotropic flux of bare $g = g_D$ massive magnetic monopoles for a catalysis cross section smaller than few mb.

In the literature one finds references to many types of MMs. For completeness we recall the simplest definitions of many of these MMs.

- *GUT monopoles* are the MMs connected with the Grand Unification of the electroweak and strong interactions and have masses of $10^{16} \div 10^{17}$ GeV. They appear in the early universe at the end of the GUT epoch [74H1], [74P1], [83F2], [84P3], [85K2]; *'t Hooft-Polyakov monopoles* are GUT MMs [90K1], [92B1], [93D1], [98K1]; *SO(3)-Z2 monopoles* are particular GUT MMs [98G4].
- *QCD monopoles* are MMs with a colour charge [98S1], [99G1].

- *BPS monopoles* are MMs appearing in the Bogomolny and Prasad-Sommerfield limit [93B2], [97B4], [97C3], [97S1], [98B2], [99I2], [99L1].
 - *Kaluza-Klein monopoles* are MMs connected with the unification of the GUT interaction with the gravitational interaction; they have typical masses $> 10^{19}$ GeV [83S3], [86S3], [97B3], [98B3].
 - *Non abelian monopoles* are MMs which appear in non abelian theories (including GUT, Kaluza-Klein,..., monopoles) [94M1], [94M2], [99C1], [00L1].
 - *Classical (Dirac) monopoles* are abelian MMs hypothesized by Dirac in 1931; they could have relatively low masses [31D1], [33T1], [51M1], [59B1], [72B2], [78Z1], [90A4], [97H1].
 - *Intermediate mass monopoles* are MMs connected with an intermediate symmetry breaking scale; they could have masses of the order of 10^{10} GeV [84L2], [95D2], [00B1], [00B2].
 - *Wu-Yang monopoles* are particular solutions in Yang-Mills theories [76W1], [98D2].
 - *Monopoles in String Theories* [93S1], [94B2], [99H1].
 - *Constituent monopoles* are MMs formed by the superposition of n BPS MMs (for a $SU(n)$ gauge group) [98K2], [99K1].
 - *Complex monopoles* are solutions of Yang-Mills theories when adding a Chern-Simons term [98T1], [99H2], [99T1].
- For further possibilities, see other references, such as [98L2], [99F1], [99T2].

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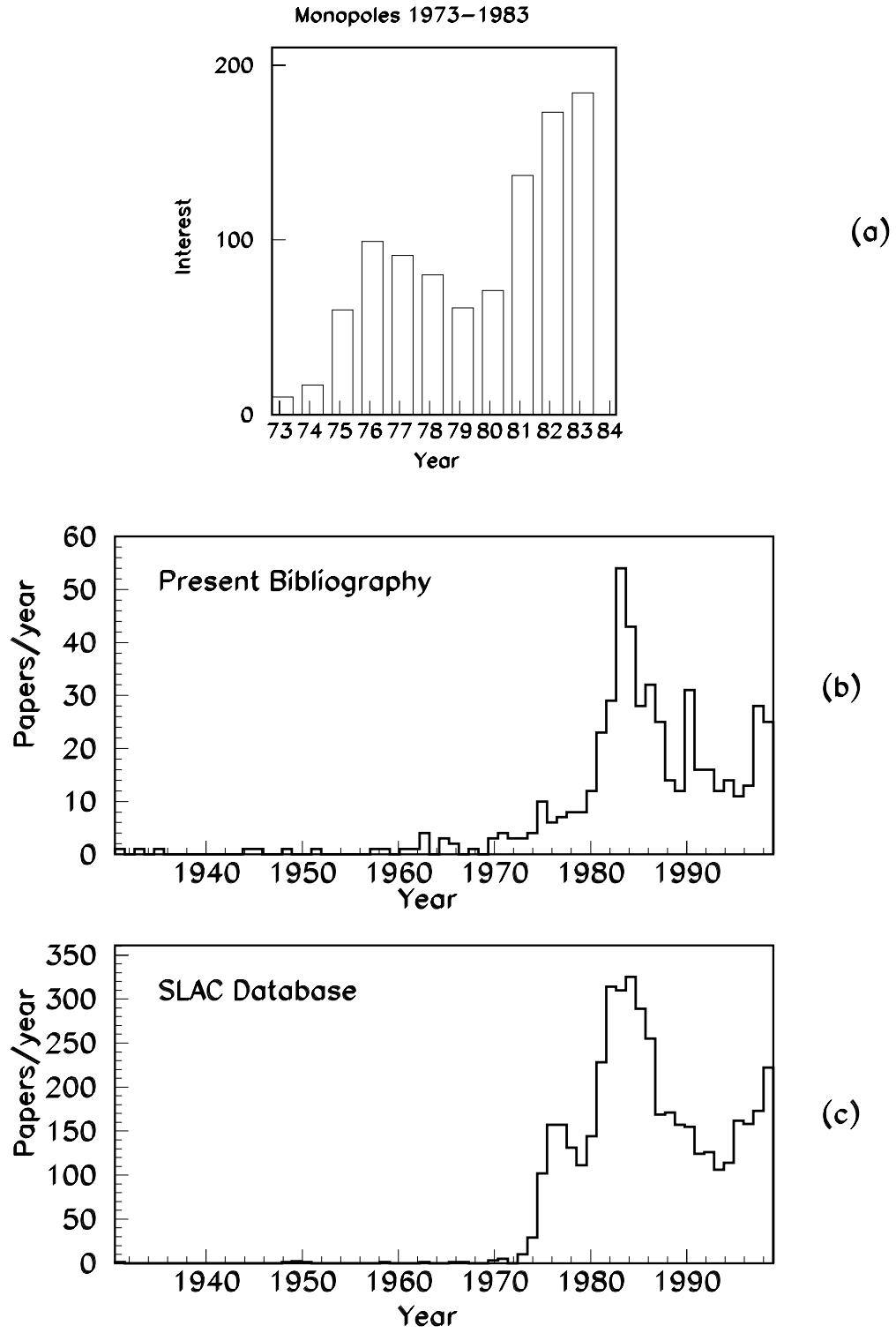


Figure 1: (a) The upper hystogram shows the yearly number of papers on MMs published from 1973 till 1983 [83P1]. (b) The middle hystogram shows the number of papers of the present bibliography as a function of the year of publication. (c) The lower hystogram shows the yearly number of papers found in the SLAC database with the search command *find title monopole# or title dyon# or keyword magnetic monopole* as a function of the year of entry in the database.

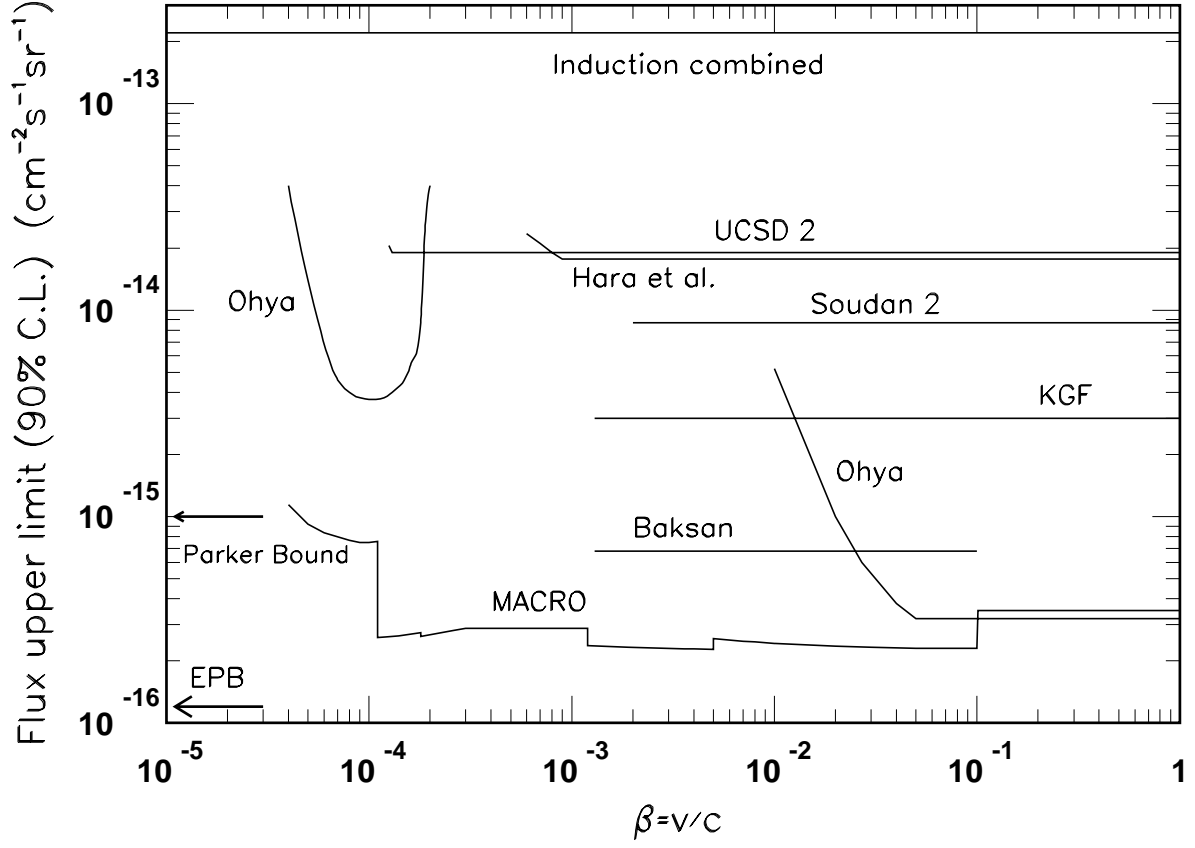


Figure 2: 90% C.L. upper limits on an isotropic flux of $g = g_D$, massive magnetic monopoles in the cosmic radiation, assuming a catalysis cross section smaller than a few mb [97A4], [97G2]. The limits are now regularly updated.